Evaluation of Warm Cloud Microphysical Processes in Global Climate Models with Multi-Sensor Satellite Observations

Kentaroh Suzuki (University of Tokyo), Jean-Christophe Golaz (NOAA GFDL), Huan Guo (NOAA GFDL), Peter Bogenschutz (NCAR)

I.   Abstract

In this investigation, we will evaluate microphysical processes of warm liquid clouds in global climate models with multi-sensor satellite observations, in response to the Modeling, Analysis, Prediction and Projection (MAPP) competition of "Process-oriented evaluation of climate and Earth system models and derived projections" within Area A "Metrics for climate and Earth system model development" and of Type 2 "Research teams developing process-oriented metrics." Warm cloud microphysics is one of the most uncertain components in global climate models and is also a major pathway through which aerosols influence the clouds and climate, referred to as the aerosol indirect effect. The objective of the research is to: (i) develop observation-based metrics that dictate key signatures of the warm rain microphysical processes with a combined use of the CloudSat/A-Train multi-sensor satellite observation products, (ii) apply the methodologies to climate models to identify fundamental biases in the representation of key microphysical processes that are crucial for estimates of the aerosol indirect radiative forcing and thus for climate projections, and (iii) propose improvements of microphysical parameterizations in such models for a better representation of warm cloud processes and more reliable estimates of the aerosol indirect radiative forcing.

Previous studies by the PI devised new methodologies for analyzing the CloudSat/A-Train multi-sensor satellite observations to "fingerprint" warm cloud microphysical processes and also applied them to cloud-resolving and climate models to identify fundamental model biases in representing the processes. This investigation will extend such model diagnostic approaches to systematic analysis of global climate models. For this purpose, we plan to: (i) integrate the new PI-developed methodologies as a unified set of observation-based, process-oriented metrics that "fingerprint" the fundamental process signatures of warm cloud microphysics, and (ii) apply the metrics to results from multiple climate models including GFDL Climate Model version 3 (CM3) and NCAR Community Atmosphere Model version 5 (CAM5) for their process-oriented evaluations. Furthermore, (iii) systematic sensitivity experiments with GFDL CM3 or its atmospheric component, AM3, will be conducted to examine how different assumptions and configurations in microphysics parameterization schemes influence the model representation of the process in the form of the new metrics. Through these analyses, we intend to offer a process-based constraint on fundamental uncertainty in climate models in an attempt to improve the microphysical process representations. A particular emphasis will be placed on mitigation of the dichotomy found in the investigators' previous study between such a process-based model constraint and the historical temperature reproducibility in GFDL CM3.

The proposed research will directly contribute to the specific objective of the Competition aiming at "process-oriented evaluations of climate and Earth system models and derived projections". In particular, we intend to substantially mitigate the uncertainties in aerosol indirect radiative forcing arising from fundamental uncertainties in model representation of cloud microphysical processes for more reliable climate projections of global temperature and precipitation. The proposed research will thus contribute to NOAA's long-term climate goal through addressing the core activities of "understanding and modeling" and "predictions and projections" and the societal challenges of "climate impacts on water resources".

Process Oriented Diagnostics of Tropical Cyclones in Climate Models

Suzana Camargo (Columbia University), Adam Sobel (Columbia University), Daehyun Kim (University of Washington), Anthony D. Del Genio (NASA GISS)

Abstract:

The simulation of tropical cyclone (TC) activity in climate models is still a challenging problem. While some models are able to simulate TC activity with characteristics very similar to those observed, many models have very strong biases. While increasing horizontal resolution often improves the characteristics of model TCs, resolution alone is not sufficient for high skill in simulating TC activity. We propose here a suite of process-based diagnostics to identify model characteristics that are responsible for a good simulation of TCs in global atmospheric and ocean-atmosphere coupled climate models, including high-resolution global models which have become increasingly used for studies of the relationship between TCs and climate.

First, we will examine the role of large-scale environmental variables, such as vertical wind shear and potential intensity as well as various integrated genesis indices, with standard TC activity measures. Second, we will develop and test process-based diagnostics to investigate the influence of model physics on TC formation in the models. As there are some similarities between the processes involved in the Madden-Julian Oscillation (MJO) and tropical cyclogenesis, our proposed diagnostics are heavily influenced by the process-based diagnostics that were developed for the MJO and that have led to an improved understanding of how model physics controls the MJO simulation. These diagnostics focus on how convection, moisture, clouds and related processes are coupled at individual grid points, and give information about how the convective parameterizations interact with resolved model dynamics. Our working hypothesis is that similar interactions are important for tropical cyclone genesis and intensification in models, and we will test that hypothesis. Third, we will use standard wave diagnostics to identify the Madden-Julian Oscillation and various convectively coupled tropical in the models, and relate these to standard TC activity diagnostics, to determine how well the models simulate the association between TCs and these disturbances which are known to modulate TC genesis in observations. In the fourth and final part of our project, we will perform parameter sensitivity studies in which we will modify the physics of a climate model, the National Aeronautic and Space Administration Goddard Institute for Space Studies (NASA GISS) model, and analyze how the simulated TC activity is affected. This approach will allow us to explore the physics parameter space in a more controlled fashion than is possible with existing model ensembles of opportunity. In the first three phases, the project will use existing multi-model databases, including those from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and US CLIVAR Hurricane Working Group, as well as additional simulations and model output from our collaborators from NASA GISS, National Oceanographic Atmospheric Administration – Geophysical Fluid Dynamics Laboratory (NOAA-GFDL), in Princeton, NJ and the Istituto Nazionale di Geofisica e Vulcanologia – Centro Euro-Mediterraneo sui Cambiamenti Climatici (INGV-CMCC), in Bologna, Italy.

This project fits well within the MAPP process-oriented evaluation of climate models, by developing new diagnostics to evaluate model performance in simulating tropical cyclones. The knowledge gained with these diagnostics can then be used in improving the next generation of climate models. This project fits well with NOAA's long-term climate goals, given the large impacts of tropical cyclones in the U.S. and the importance of making robust projections of future tropical cyclone activity.

James Booth (City University of New York, City College), Catherine Naud (Columbia University), Zhengzhao Luo (City University of New York, City College), Jean-Christophe Golaz (NOAA GFDL)

2. Abstract

Title: Metrics for general circulation model biases in extratropical cyclone clouds and precipitation: evaluating their skill and identifying processes to be improved.
PI: James F. Booth Climate/Weather Research Group

Abstract

The general circulation models that participate in the CMIP5 exercise exhibit cloud and precipitation biases in the midlatitudes, a region where extratropical cyclones play an active role. This in turn causes long-term biases for the prediction of average and extreme precipitation events, as well as the global energy balance. It is thus paramount to better understand which processes in the models contribute to these biases and provide a set of metrics to help in their evaluation.

As such, the objective of this project is to create a set of process-oriented metrics to evaluate model ability to produce realistic extratropical cyclones. These metrics encompass the characteristics of the storms on the planetary, synoptic and frontal scales. The metrics are designed to inform on model skill in accurately representing the large-scale and the cyclone-scale dynamics, as well as the cyclone moisture content, temperature, cloud and radiation fields and precipitation. Furthermore, the proposed analysis methods will help identify the limitations of current parameterization schemes.

This project is based on a set of tools that the team has developed over the years that use model gridded outputs to: (a) locate and track extratropical cyclones, (b) locate the warm and cold fronts, (c) measure cyclone-local characteristics through the use of compositing techniques and (d) use conditional subsetting to identify the sensitivity of cyclone cloud and precipitation to changes in dynamics and thermodynamics. It also combines a comprehensive set of satellite observations and reanalysis output using both state-of-the-art and innovative approaches to assess models beyond the simple map-to-map comparison. The metrics will provide (1) a measure of a model's ability to reproduce the atmospheric conditions within the storms, and (2) the model's ability to predict the right response in cloud and precipitation to changes in atmospheric conditions. Furthermore, specific metrics are designed to inform on the reliability of components of the model that directly participate in the formation of clouds and precipitation, namely their convection, cloud and boundary layer schemes.

The outcome of the project will be a package of numerical codes that generate the process-based metrics proposed herein and compare them with reference metrics. The reference metrics are a series of storm-specific observations and reanalysis products that we will generate. Additionally, in our work we will test the process-based metrics using output from the GCMs participating in CMIP5. Both the numerical code for the metrics analysis and the data for the reference metrics will be made freely accessible via NOAA-CREST website.

The project directly addresses the objectives of the NOAA MAPP-Process-Oriented Evaluation of Climate and Earth System Models and Derived Projections (ID 2488569) call, namely to *"develop and integrate process-oriented metrics into U.S. modeling centers' diagnostic packages to support the evaluation and development of next-generation climate and Earth system models"*. This project fits within NOAA's long term goal of "Climate Adaption and Mitigation" by addressing their objective of "Improved scientific understanding of the changing climate system and its impacts" and "Assessments of current and future states of the climate system".

Hariharasubramanian Annamalai (University of Hawaii), Arun Kumar (NOAA CPC)

Development of process-oriented metrics for ENSO-induced teleconnection over North America and U.S. Affiliated Pacific Islands in Climate models

H. Annamalai[1], and Arun Kumar[2]

1. International Pacific Research Center (IPRC), University of Hawaii
2. Climate Prediction Center, NOAA, Washington DC

Abstract

In climate models, to demonstrate the hypothesis that the sea surface temperature (SST) anomalies associated with ENSO serves as the source predictability of seasonal to interannual climate anomalies over North America and U.S. affiliated Pacific Islands (USAPI) require translating these SST anomalies into precipitation and latent heating anomalies by models' physical parameterizations. While CMIP5 (Coupled Model Intercomparison Project Phase 5) assessment studies suggest certain improvement in representing ENSO-related SST anomalies, representation of precipitation anomalies along the equatorial central Pacific and therefore tropical to extratropical teleconnection have not improved. **Climate models' fidelity in representing ENSO and associated teleconnection require detailed assessment of models' ability in representing "moist convective processes". Specifically, during the life-cycle of ENSO, a detailed evaluation of various entropy elements in forcing convection and factors that determine vertical structure of diabatic heating (such as cloud intensity and height) needs to be performed. Such a process-oriented diagnostics will lead to identification of source of model errors and provide pathways for model improvement.**

We propose processes-oriented metrics to be applied on the 45+ CMIP5 models as well as on the hindcasts performed with the North American Multi-Model Ensemble Phase 2 (NMME-2). To assess observational uncertainty, similar metrics will be obtained from all available reanalysis products (CFSR, NCEP, ERA-Interim, JRA-25 and MERRA). We identify 4 major objectives that deem highly relevant to the present focus. Diagnostics are developed to understand: (i) processes that shape tropical precipitation climatology; (ii) processes in determining precipitation anomalies during different phases of ENSO and their different roles between equatorial central vs eastern Pacific precipitation anomalies; (iii) processes that determine the vertical structure of diabatic heating anomalies and associated teleconnection, and (iv) processes that account for regional and remote precipitation anomalies. **Deliverables include objectively oriented and physically based metrics for climate models' performance in representing precipitation anomalies along the equatorial Pacific, North America and the USAPI.**

Our goals lie in identifying sources of model errors in physical parameterization, and provide clear pathways for model improvement. Our proposed research targets the MAPP competition that focuses on "Process-oriented evaluation of climate and Earth system models and derived projections". Specifically, the competition identified research focus - *"Area A: Metrics for climate and Earth system model development"*. Process-based diagnostics will lead to selection of a subset models could contribute to other crosscutting (RISA and National climate change assessment) programs of NOAA

Process oriented metrics of land-surface-atmospheric interactions for diagnosing coupled model simulations of land surface hydro-meteorological extremes

Justin Sheffield (Princeton University)

2. ABSTRACT

Title: Process orientated metrics of land surface-atmospheric interactions for diagnosing coupled model simulations of land surface hydro-meteorological extremes
PI: Justin Sheffield, (justin@princeton.edu), Princeton University.
Competition: MAPP – Process-Oriented Evaluation of Climate and Earth System Models and Derived Projections, Competition ID: 2488569, Area A – Type 2

Introduction to the Problem: Hydro-meteorological extremes such as droughts and heat waves have enormous impacts on water resources, agriculture, health, energy production and infrastructure. Understanding how these events have varied in the past and how they are expected to change in the future are key to mitigation and adaptation. Land-atmosphere (L-A) interactions and feedbacks are increasingly acknowledged as important processes that contribute to climate variability and can amplify droughts and heat waves through changes in partitioning of surface fluxes and interactions with the atmospheric boundary layer. Climate models are central to understanding future changes, but they continue to show problems in depicting climate extremes and the processes that lead to their development and persistence, despite incremental improvements in model resolution and more comprehensive treatment of physical processes. Their future projections are therefore inherently uncertain, especially as L-A interactions are expected to intensify in the future and play a more important role in modulating these extremes.
Rationale: Given the potential for high impacts of droughts and heat waves, and our general lack of understanding of future changes in these extreme events, there is a pressing need to evaluate coupled models for their representation of surface fluxes and L-A interactions at the process level. ***We propose to develop and test a suite of process-based metrics to diagnose the coupling and feedbacks between the land and the atmosphere, and apply these to climate models to help identify deficiencies in parameterizations.*** This has potential to improve our understanding of the contribution of the land to climate variability and its role in amplifying extreme events, as well as to lead to model developments that provide better understanding of past changes and reduction of uncertainties in future projected changes. This work leverages from the PI's experience and ongoing activities in understanding large-scale variability of the land surface and its feedbacks with climate, particularly changes in extreme events.
Summary of work to be completed: We will evaluate the observational uncertainties in surface climate, hydrology and L-A interactions from it-situ, remote sensing and observationally constrained models, globally, with a focus on the U.S. We will develop and test a suite of process-based diagnostic metrics on the observational data, with a focus on droughts and heat waves. These metrics will be applied to the CMIP5 ensemble for the historical simulation and a set of future scenarios. The metrics will be used to identify deficiencies in coupled model parameterizations, attribute historic and future changes to L-A interactions, and link the robustness of future projections to historic performance.
Relevance to the Competition and NOAA's long-term climate goal: This work is central to the mission of the Climate Program Office's MAPP program to "*enhance the Nation's capability to predict variability and change in Earth's climate system*" by focusing on improvement of climate models in the realm of L-A interactions that is not well understood but is increasingly acknowledged as being important. As such it directly adheres to NOAA's long-term climate goal of adaptation and mitigation, by specifically addressing the goal to "*improve scientific understanding of the changing climate system and its impacts*" by evaluating coupled climate models at the process level so that past changes can be diagnosed and the uncertainties in future changes evaluated.

Xianan Jiang (UCLA); Eric Maloney (Colorado State University), Ming Zhao (NOAA GFDL), Shian-Jiann Lin (NOAA GFDL)

<u>Process-oriented Diagnosis and Metrics Development for the Madden-Julian Oscillation Based on Climate Simulations</u>

Xianan Jiang[1], Eric Maloney[2], Ming Zhao[3], and Shian-Jiann Lin[3]

[1]Joint Institute for Regional Earth System & Engineering/UCLA, Los Angeles, CA
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Total Proposed Cost: UCLA $419k (with CSU 150K), GFDL $95k; **Period:** 08/01/2015-07/31/2018

Summary

The Madden-Julian Oscillation (MJO) exerts significant influences on global climate and weather including in North America, and serves as a critical basis of the "Seamless Prediction" concept by bridging the forecasting gap between medium- to long-range weather forecasts and short-term climate prediction. The MJO, however, remains poorly represented in state-of-the-art general circulation models (GCMs) as well as NWP models, which leaves us greatly disadvantaged in undertaking climate change studies, particularly in projecting future changes in extreme events that are significantly modulated by the MJO.

In this proposed study, built upon both the PI's (Jiang, co-organizer of the MJOTF/GASS MJO Project) and Co-PI's (Maloney, co-chair of the WGNE MJO Task Force and NOAA MAPP CMIP5 Task Force) extensive experiences in studies on process-oriented metrics for the MJO, as well as the co-I's (Zhao) and collaborator's (Lin) expertises in GFDL model development, we propose to further explore key physical processes for realistic MJO simulations in GCMs by diagnosing observations and multi-model simulations including the 27 model datasets collected from the MJO Task Force/GASS MJO project and GFDL GCM simulations. In particular, we plan to comprehensively evaluate several processes previously considered to be important for the MJO, including feedbacks between environmental moisture and convection, convection and its induced circulation, and cloud-induced radiative heating and convection. Findings from this project will be developed into effective process-oriented metrics to assess reasons for MJO fidelity and particularly provide insight into key GCM deficiencies in MJO simulations, which further will provide valuable guidance for model development. These metrics will be built into standard software packages as part of collective efforts coordinated by the Type-1 project, and be installed at GFDL and other modeling centers. This proposed work will significantly contribute to GFDL's model development efforts related to CMIP6 and IPCC AR6, particularly regarding representation of the MJO.

This proposal is strongly relevant to one of the NOAA NGSP's long-term goal, *"toward an improved scientific understanding of the changing climate system",* by advancing core capabilities in *"understanding and modeling"* and *"predictions and projections"*, as well as societal challenges in *"climate impacts on water resources"* and *"changes in extremes of weather and climate"*. In particular, this proposal directly addresses MAPP Program's FY15 goal for *"Process oriented evaluation of climate and Earth system models and derived projections"*, particularly in the **Area A**: *"Metrics for climate and Earth system model development",* as a type-2 subproject with the specific focus on the MJO.

Development of a Framework for Process-Oriented Diagnosis of Global Models

Eric Maloney (Colorado State University), Yi Ming (NOAA GFDL), Andrew Gettelman (NCAR), David Neelin (UCLA)

B. Abstract: A critical need exists to improve the diagnosis of global climate and forecasting models. For example, models continue to be plagued by common biases in tropical convection and its variability, including well-known trade-offs between the quality of the mean state and of intraseasonal convective variability such as the Madden Julian Oscillation (MJO). A key need is incorporation of process-oriented diagnostics into standard diagnostics packages that can be applied to development versions of the models, allowing the application of diagnostics to be repeatable across multiple model versions. A significant barrier is the lack of a mechanism for getting community-developed diagnostics into the modeling center development process. The proposed work involves close collaboration between diagnostic developers and modeling centers to develop a common and extensible mechanism for rapid dissemination of process-oriented diagnostics across modeling centers. As demonstration of the process, we will implement critical diagnostics for tropical convection and its variability.

Proposed goals will be met as follows:

1) A leadership team with diagnostic developers and software developers at GFDL and NCAR will be formed to develop best practices for implementation of diagnostics into the centers' standard evaluation packages.

2) GFDL and NCAR will coordinate development of a software framework that allows sharing of diagnostics, with an eye to extensibility to other centers (and other diagnostics) during the project lifetime. This coordinated effort will include development of software tools/standards that individual PIs may use to craft their diagnostics into a form easily useable by multiple modeling centers.

3) Initial emphasis will be placed on process-oriented diagnostics related to tropical convection and its variability. The modeling centers have a critical need for diagnostics in this area, making this topic an attractive one for a pilot diagnostics effort. PIs Maloney and Neelin have led development of existing process-oriented diagnostics that will serve as initial test diagnostics for this effort. Continued development of tropical convection diagnostics will also form a key component of the proposed work.

4) The PIs will also coordinate with international efforts that are developing general diagnostics frameworks such as those at PCMDI and the European EMBRACE project, to ensure that the efforts developed here are complementary rather than duplicative of these efforts.

5) This proposal will also provide a mechanism for PIs of the Type 2 proposals funded under this MAPP call to incorporate their new diagnostics into the diagnostics stream of modeling centers. The PIs have developed collaborations with several potential Type 2 PIs at the proposal stage to aid this integration.

Relevance to NOAA: This proposal directly addresses the FFO *"MAPP - Process-oriented evaluation of climate and Earth system models and derived projections"* by developing a Type 1 core team to lead development of a mechanism for inclusion of process-oriented diagnostics into standard packages of modeling centers, and also conducting scientific development of new process-oriented diagnostics. We will aid NOAA's NGSP by improving models to provide more accurate "assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions."

Aiguo Dai (University at Albany), Jean-Christophe Golaz (NOAA GFDL), Junhong Wang (University at Albany), Ming Zhao (NOAA GFDL)

MAPP Competition: Process-oriented evaluation of climate and Earth system models and derived projections (Area A, Type 2)

1. Abstract

The diurnal cycle is a fundamental feature of Earth's climate. Because of its short time scales and close coupling to surface and atmospheric processes, the simulation of the diurnal cycle provides an ideal test bed for evaluating many aspects of model physics. Despite recent improvements in model resolution and parameterizations, the diurnal amplitude and phase in surface temperature, cloudiness, convection, precipitation and other fields still differ considerably from observations in many climate models. These diurnal biases reflect deficiencies in various physical processes simulated by the models. While there exist many observational datasets with sub-daily resolution, most of them cannot be readily used to evaluate models, and current model evaluation packages often contain very limited data for evaluating the diurnal cycle. Based on our previous work on studying the diurnal cycle and its simulation in models, here we propose to **a) develop a new set of diurnal metrics and link them to specific underlying processes for evaluating model physics, and b) apply the diurnal metrics to diagnose and identify deficiencies in the GFDL and other CMIP5 models.**

Specifically, we propose to **1)** compile a new dataset with high temporal-resolution (hourly to 6-hourly) from surface and satellite observations, field experiments, research sites, and atmospheric reanalyses for studying the diurnal cycle and evaluating models; **2)** apply the new dataset to quantify the diurnal cycle and study its underlying processes in various fields over the globe, including surface daily maximum (Tmax) and minimum (Tmin) temperatures, precipitation frequency, intensity and amount, cloud cover, humidity and others; **3)** design a new set of effective diurnal metrics and link them to specific physical processes based on analyses of observational data; and **4)** apply these diurnal metrics and associated linkages to physical processes to diagnose deficiencies in GFDL and other CMIP5 models by analyzing sub-daily output from these models.

The new diurnal data set and diurnal metrics developed in this project will greatly enhance current model evaluation packages. Our second task will improve our understanding of the diurnal cycle and its underlying physical processes. This understanding is necessary for developing constructive diurnal metrics for evaluating physical processes in models, while tasks 3 and 4 will directly help improve models, especially the GFDL model.

A unique feature of this proposal is that it utilizes the expertise of the PI and others on this proposal in studying the diurnal cycle to identify specific physical processes underlying each of the major diurnal variations (e.g., in Tmax and Tmin or the low-level jet over the central U.S.), so that a modeler can use this information to examine specific areas in his/her model when a diurnal bias is found. Another strength is that it includes two leading modelers from GFDL who have a strong desire to improve the simulation of the diurnal cycle in GFDL's new models. This collaboration will lead to real model improvements.

Relevance:
This proposal is for MAPP Competition - *Process-oriented evaluation of climate and Earth system models and derived projections* (Area A, Type 2), which emphasizes projects to "*develop and apply process-oriented metrics to evaluate simulated climate phenomena with strong theoretical and observational bases*". The diurnal cycle is a well-studied, fundamental feature of Earth's climate. The focus of our diurnal metrics on the sub-daily processes and our emphasis on linking diurnal biases to underlying physical processes make our metrics truly process-oriented. We will also apply the new diurnal metrics to diagnose the simulation of the diurnal cycle in the GDFL and other models. Thus, this proposal is directly responsive to the MAPP competition. Improving climate models and our understanding of the diurnal cycle is also an important step to achieve NOAA's long-term climate goal to "*improved scientific understanding of the changing climate system and its impacts*".

Evaluation and Diagnosis of the Atlantic Meridional Overturning Circulation 3D Structure in Climate Models

Xiaobiao Xu (Florida State University), Eric Chassignet (Florida State University), Molly Baringer (NOAA AOML), Shenfu Dong (NOAA AOML)

(II) **Abstract**

The Atlantic Meridional Overturning Circulation (AMOC), with its large heat and freshwater transports and interaction with the atmosphere and sea-ice, plays a fundamental role in establishing the mean state and the temporal variability of the Earth's climate system. Existing studies have shown a wide spread of AMOC states in the current state-of-art climate models, CMIP5, and hence a better understanding of the driving mechanisms is urgently needed. The current analysis, however, typically quantifies the AMOC as one maximum volume transport streamfunction at certain latitudes. This overly simplified AMOC index, while important, is insufficient for formulating a comprehensive picture of the AMOC structure across the entire Atlantic and characterizing its fundamental role in the climate system, such as transport of heat/freshwater and water mass transformation.

Recognizing this problem, here we propose a collaborative effort to conduct more comprehensive analyses on the structure of the AMOC in climate models. The analyses are built on observational results and high-resolution ocean simulations, and include a) AMOC transport on temperature-salinity plane and density spaces across trans-Atlantic sections at different latitudes, b) water mass transformation due to surface buoyancy forcing as well as diapycnal/isopycnal mixing in the ocean interior, and c) diapycnal velocity. The overall goals are 1) to derive a better and more comprehensive diagnosis for evaluating the AMOC representation, including time mean structure and temporal variability, in current climate models, and 2) to identify and understand the key physical processes or mechanisms that lead to the wide spread of the AMOC state among the CMIP5 models as well as the AMOC variability in individual models.

This project is a direct contribution to the "Process-oriented evaluation of climate and earth system models and derived projections" in the area A: metric for climate and earth model development. The proposed analysis will help a) evaluate the AMOC structure in current earth system models, compared to observations and high-resolution models; and b) isolate the model biases on AMOC structure due to contributions from air-sea interaction and/or oceanic advection and mixing process. Both are critical for the ongoing efforts to improve our scientific understanding of the changing climate system and its impact, and to enhance our capability to predict climate variability and changes in climate and earth system models.